



ILE OSAKA

HEC-DPSSL workshop

Efficient Ceramic Nd:Cr:YAG Split-Disk Laser Amplifier

Hajime Okada

Institute of Laser Engineering, Osaka University

18 May 2006



- Development of Liquid face-cooled Ceramic Nd:Cr:YAG Split-Disk Laser Amplifier for High-energy, High-peak and High-average-power solid state laser

Application :EUV lithography, Laser Peening

	Existing technology	New technology
Laser material	Phosphates glass etc. Low thermal conductivity	YAG ceramic Material growth capability High thermal Conductivity High repetition rate
Structure of YAG amplifier	Rod amplifier Output limited by thermal effects or clear aperture size □25mmφ-100mm□	Split-disk amplifier Suppression of thermal effects High thermal stress fracture limit (10cm×10cm×1cm)
Coolant for Disk amplifier	Air cooling (N ₂) Fast flow rate for Turbulent flow Small heat capacity .1.3mJ/Kcm ³ .	Liquid cooling (fluorinert) Large heat capacity High pressure (4.18J/Kcm³)



Nd:YAG amplifier

1. Liquid face-cooling system

1.1 Analysis of wavefront distortion due to liquid cooling

→ Michelson interferometer

→ Far-field pattern variation

1.2 Compensation of wavefront distortion

→ Phase conjugation mirror

2. Amplification properties

2.1 Small-signal gain

→ Gain coefficient and Stored energy

2.2 Single-shot amplification

→ Operation of high input energy

→ Beam quality

Nd:Cr:YAG amplifier

1. Liquid face-cooling system

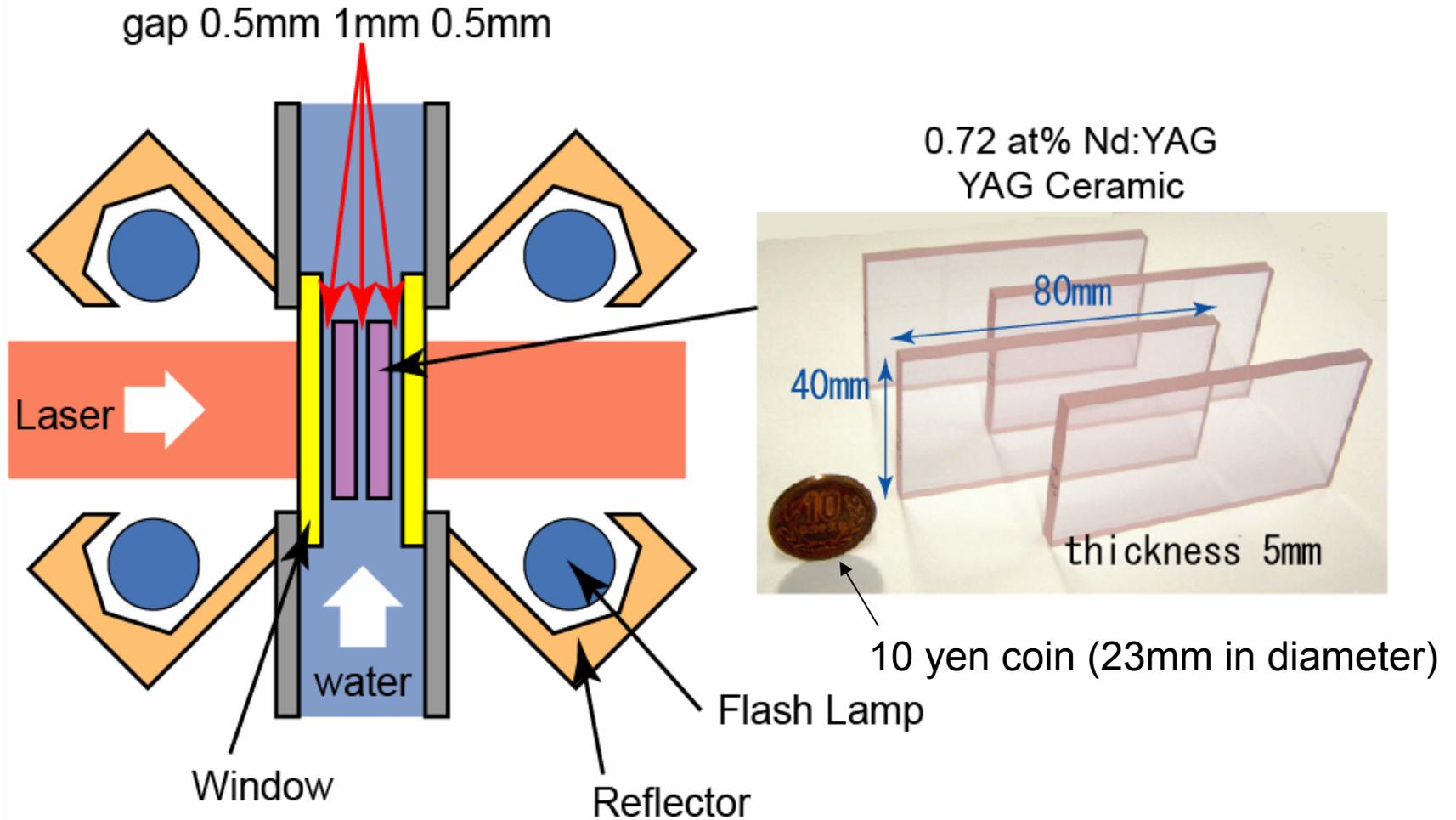
Analysis of wavefront distortion due to liquid cooling and pumping

→ Michelson interferometer

2. Amplification properties

2.1 Single-shot gain measurement

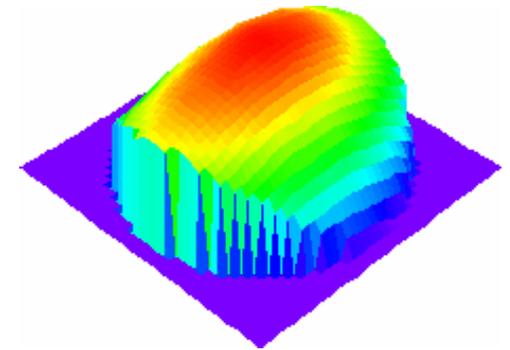
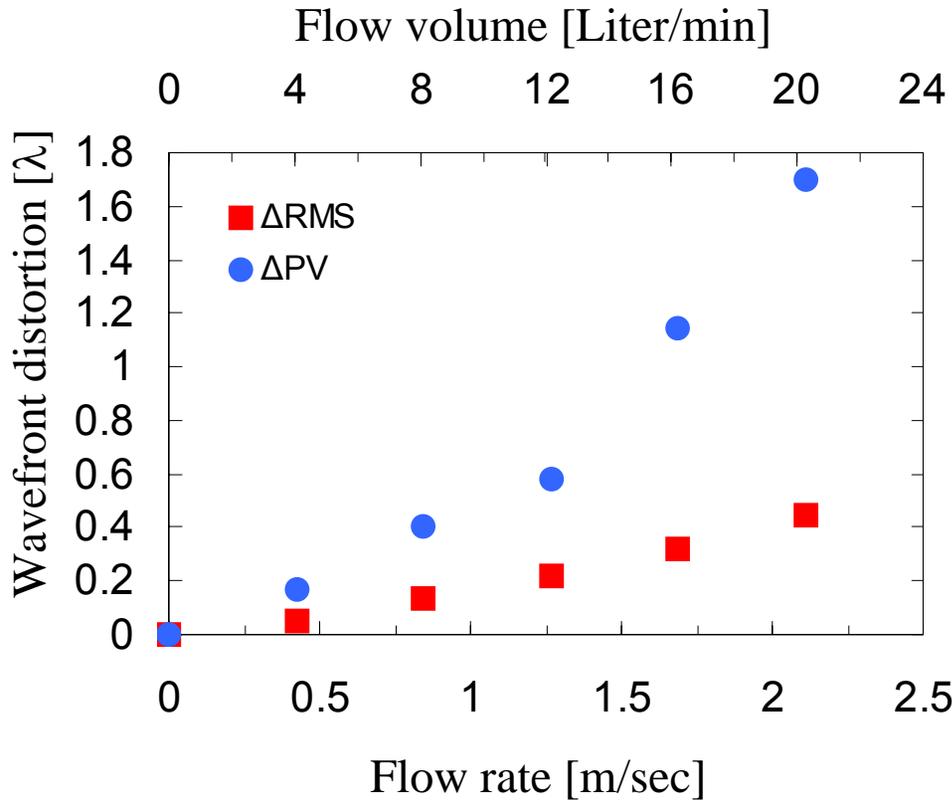
2.2 10Hz amplification



No.5 Fringe patterns by Michelson interferometer



ILE OSAKA



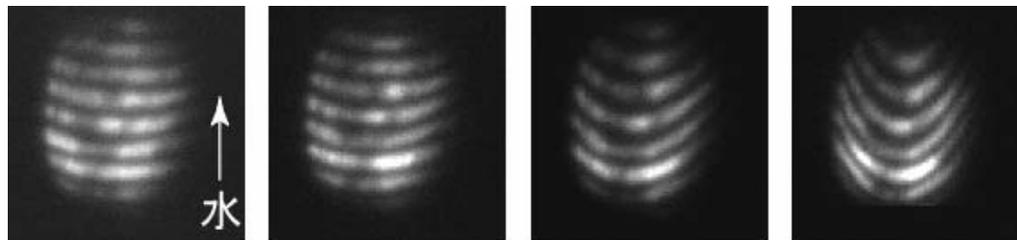
Wavefront



$$\phi(x, y)$$



Spatial phase distribution

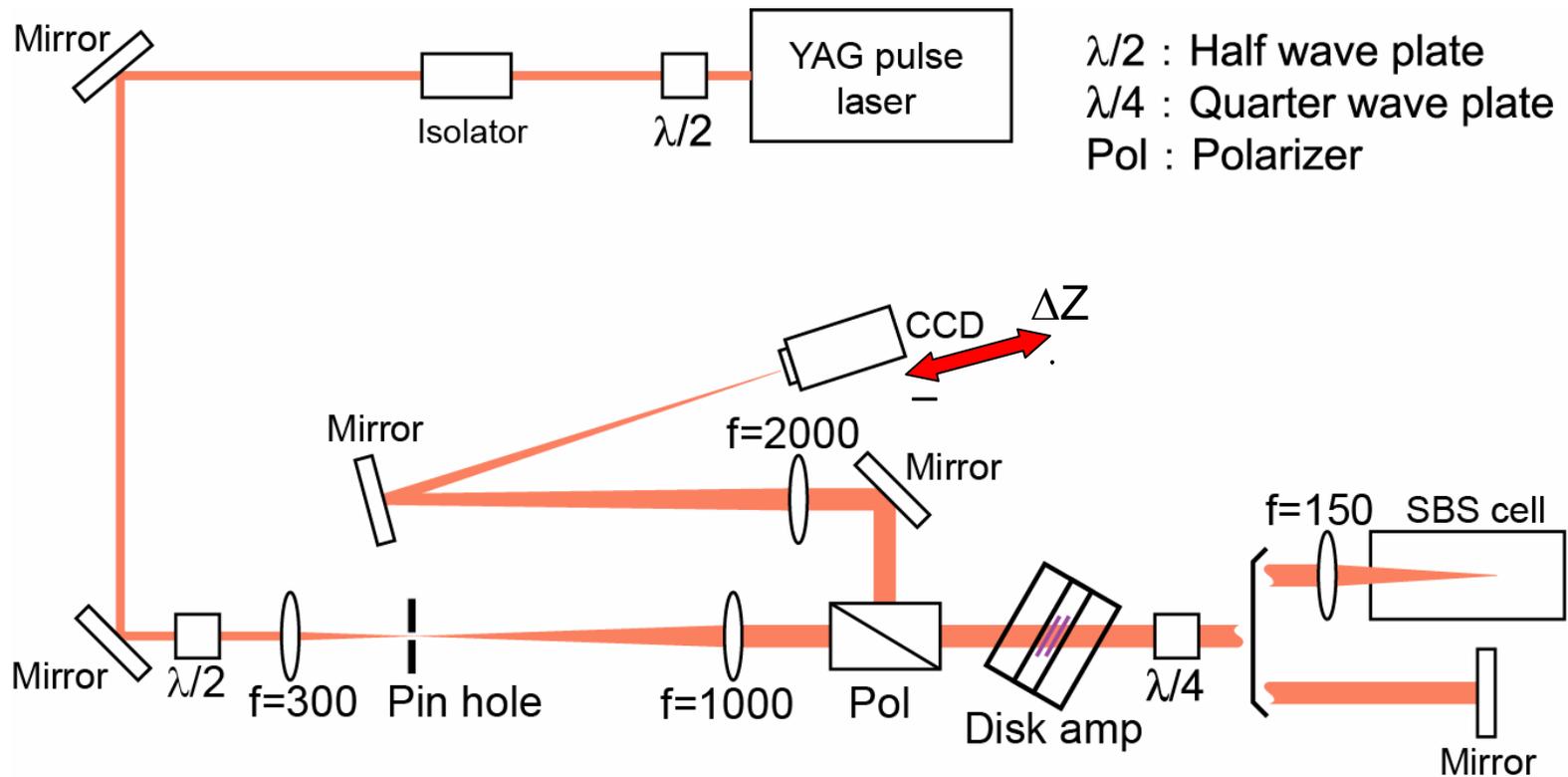


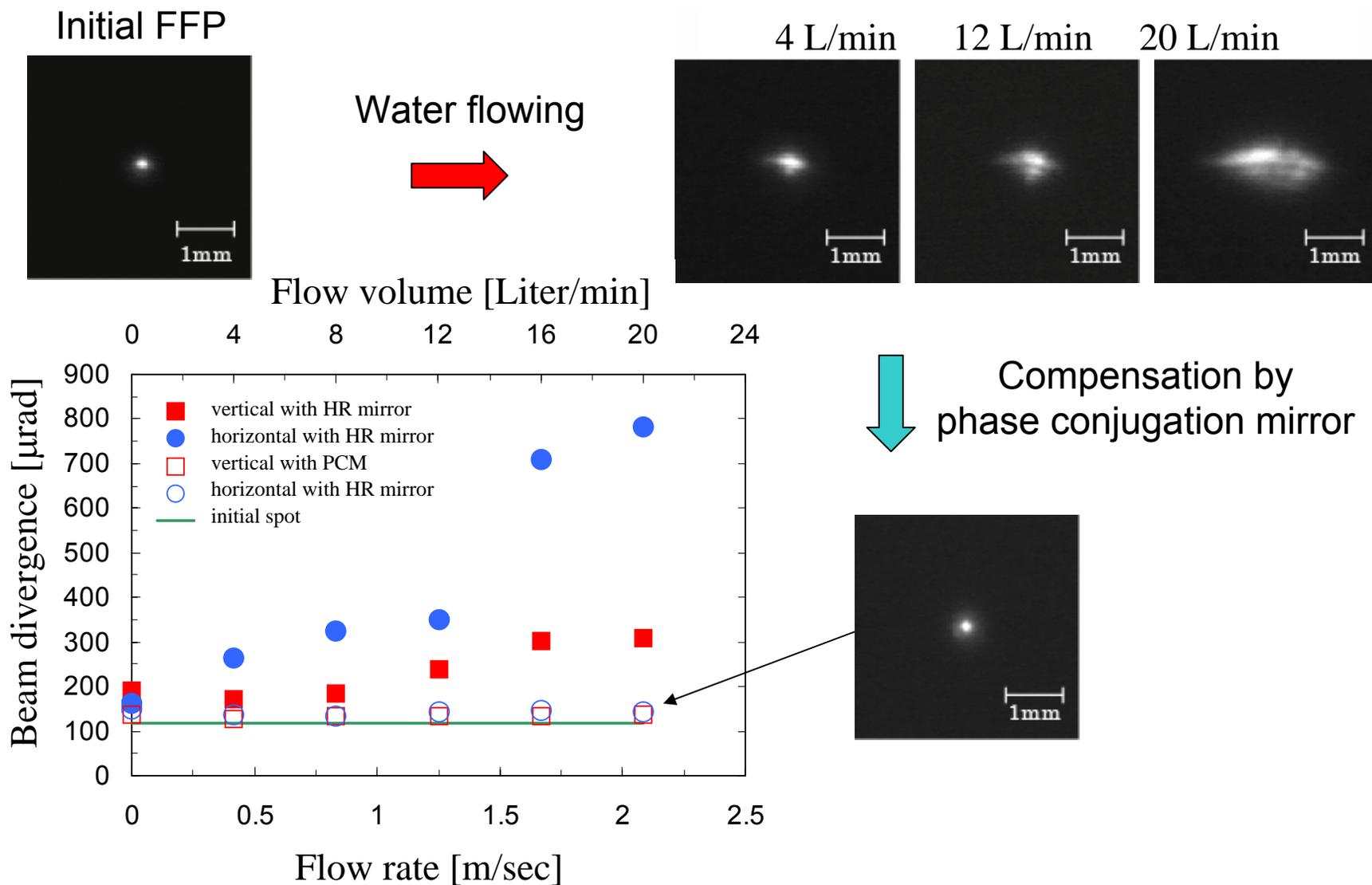
Reference 4 L/min 12 L/min 20 L/min

No.6 Experimental setup for far-field pattern measurement



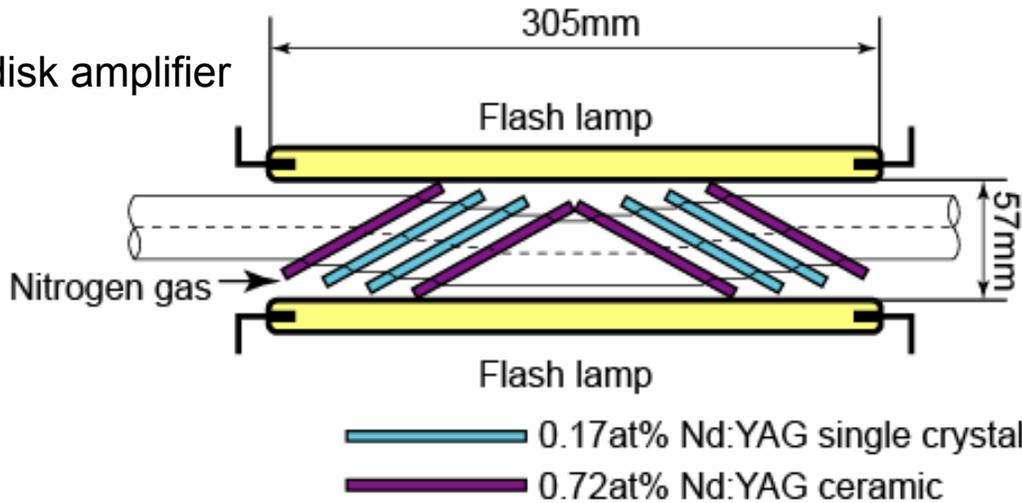
ILE OSAKA



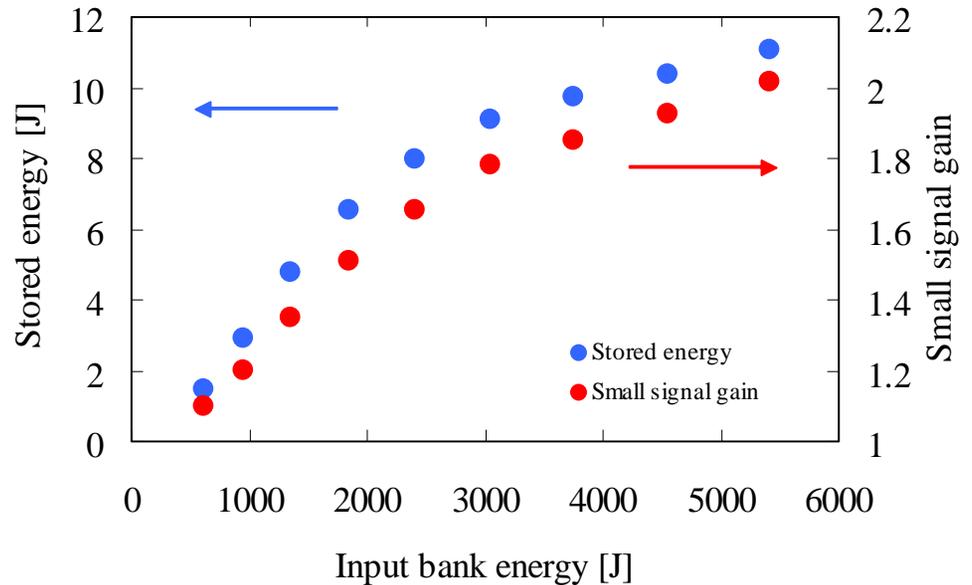


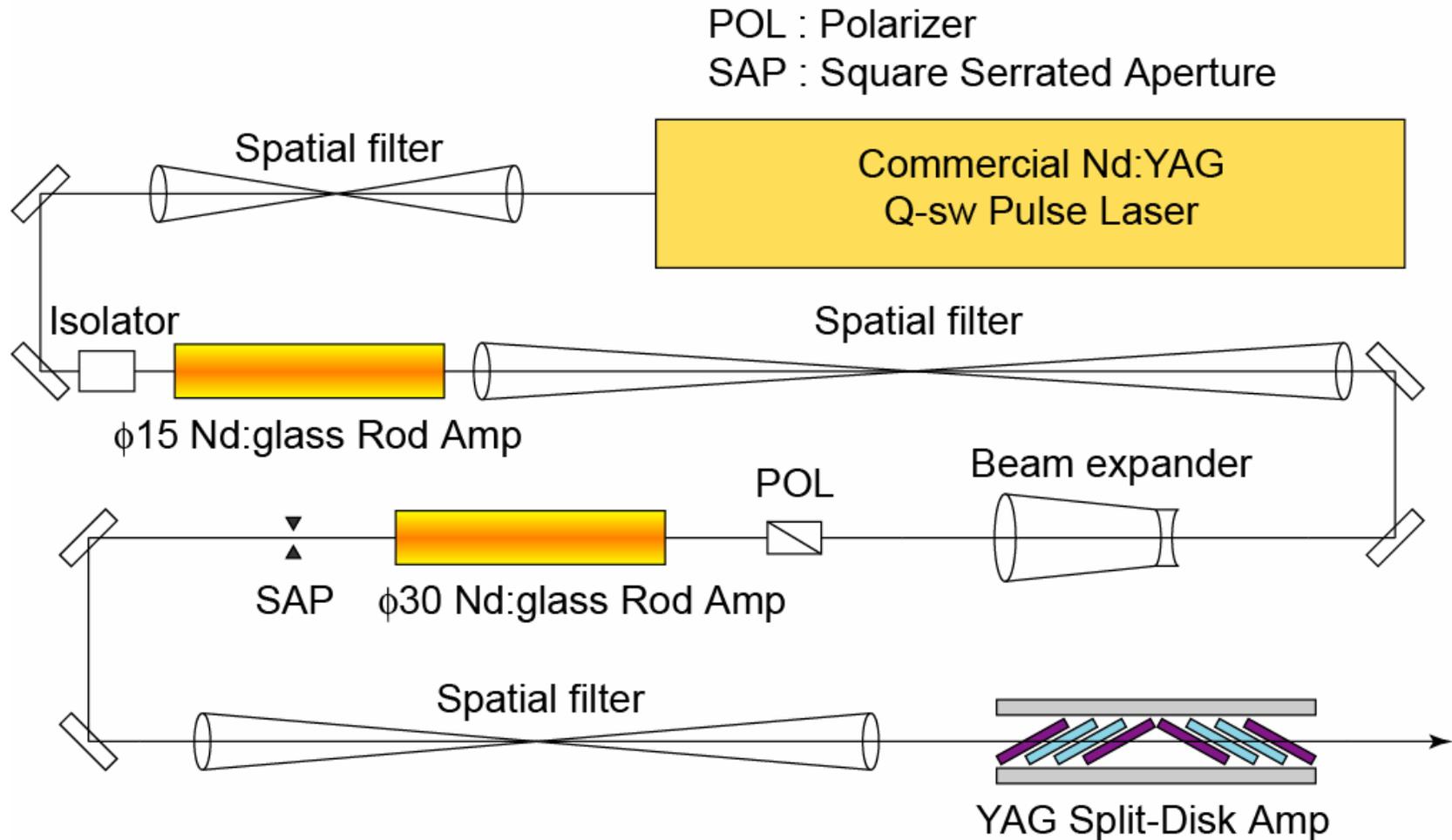


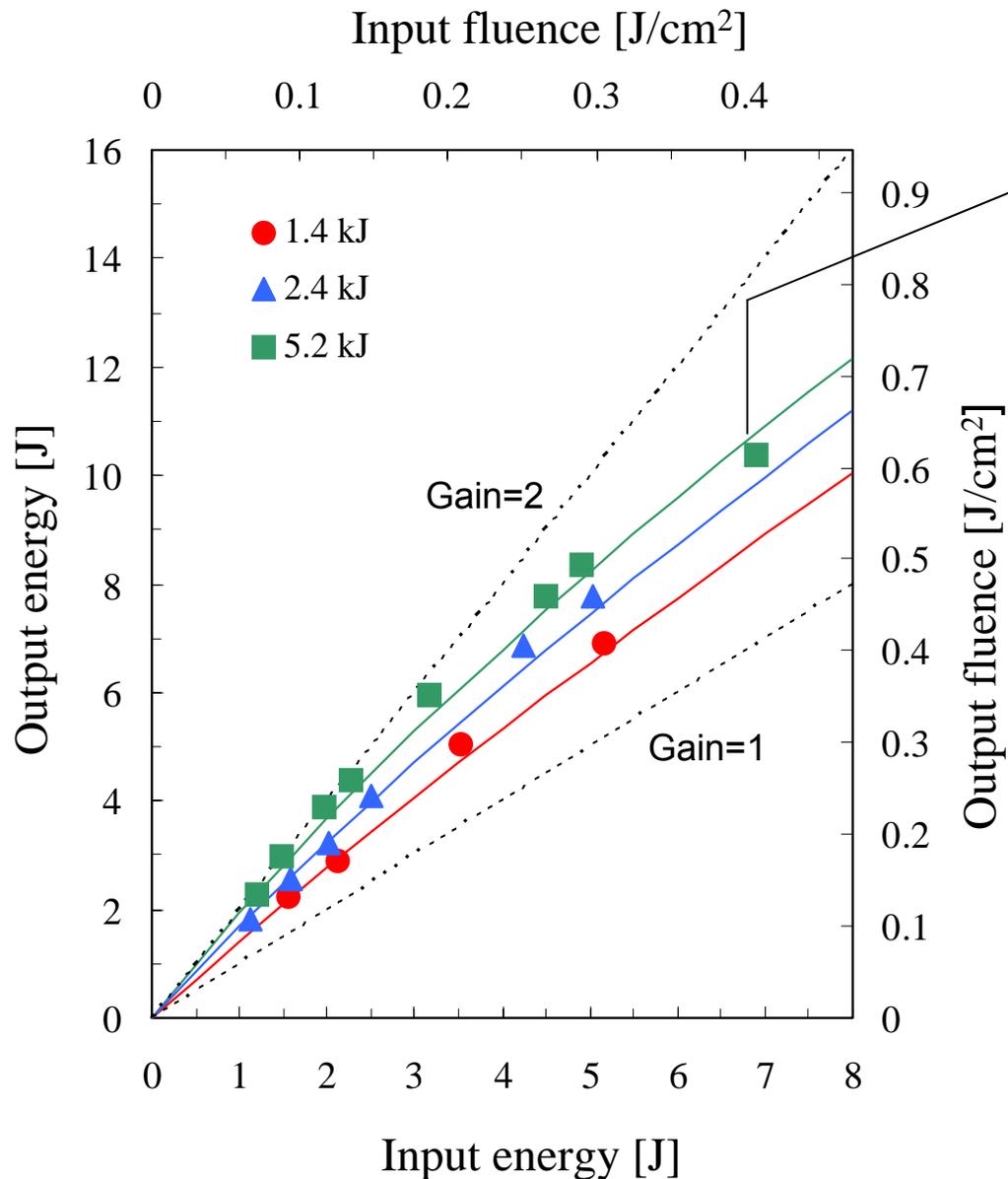
Scheme of YAG split-disk amplifier



Small-signal gain and stored energy against input bank energy







Output energy	.10.4J
Extraction efficiency	.42%
Filling factor	.71%
Signal gain	.1.5

Solid lines are theoretical value calculated from Frantz-Nodvik equation

$$E_{out} = E_S \ln \left\{ 1 + \left[\exp\left(\frac{E_{in}}{E_S}\right) - 1 \right] \exp(g_0 l) \right\}$$

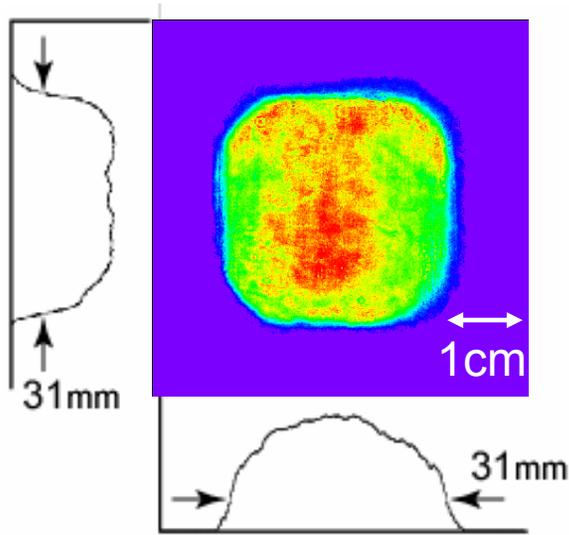
E_S : Saturation fluence

E_{in} : Input fluence

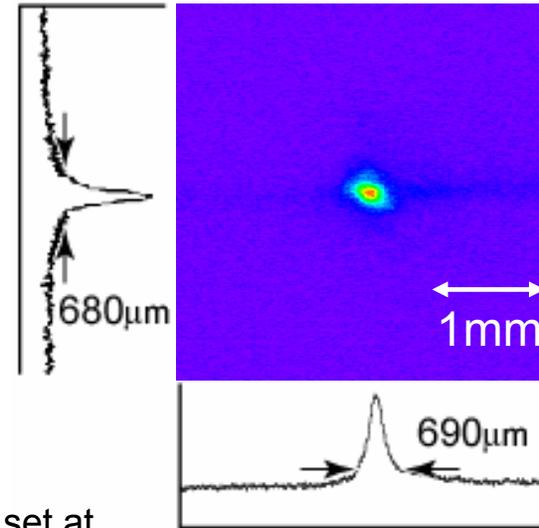
E_{out} : Output fluence



Near-Field Pattern (NFP)



Far-Field Pattern (NFP)



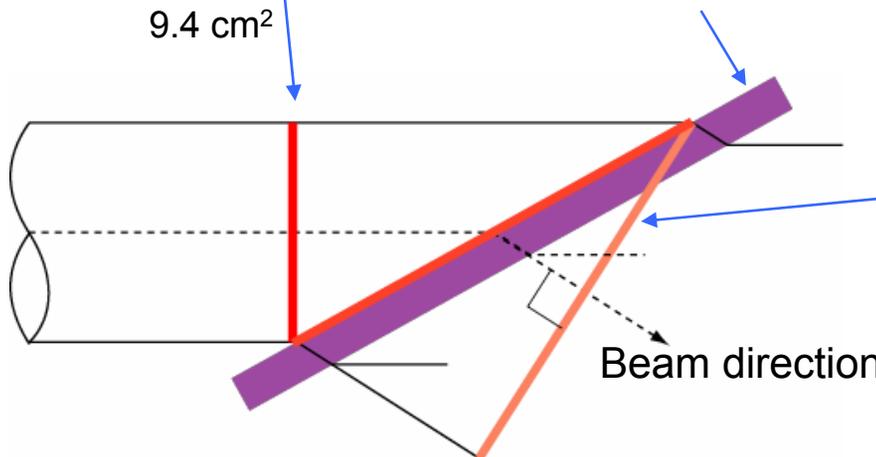
YAG ceramic set at Brewster angle

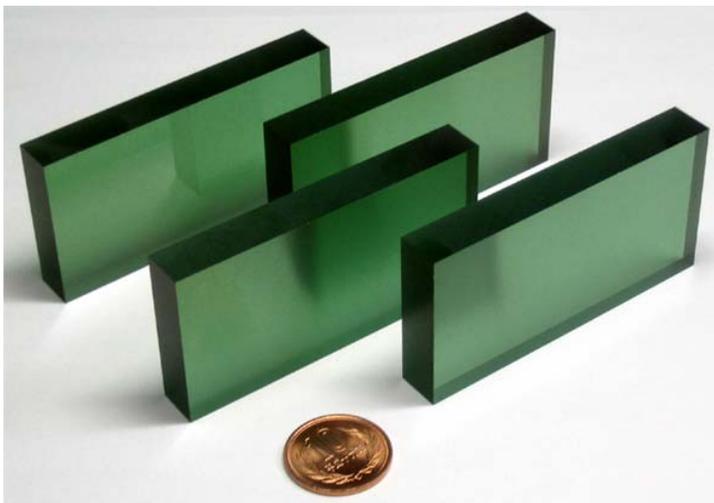
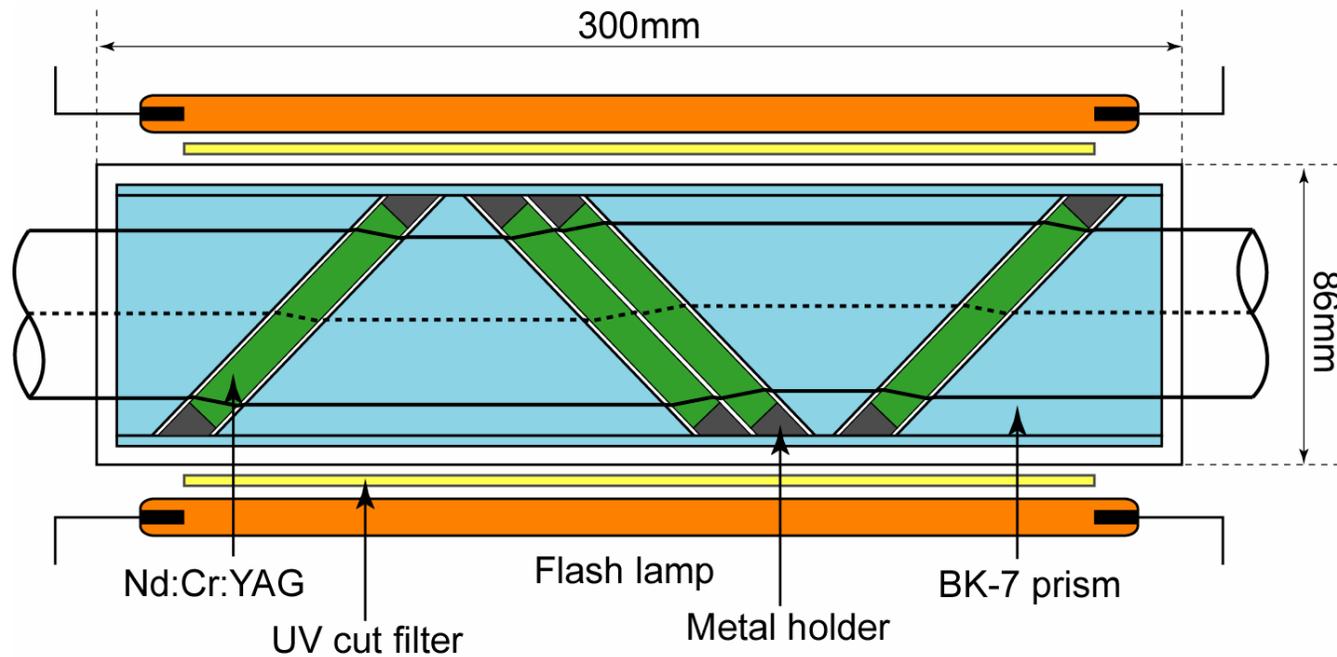
F = 88

9.4 cm²

Projected area
16.9 cm²

Beam direction





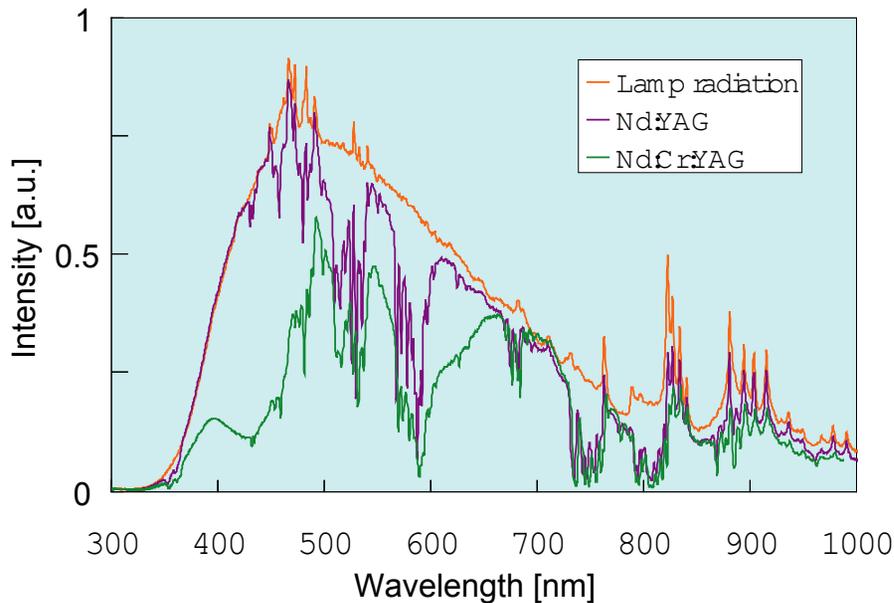
Ceramic Nd:Cr:YAG
Nd: 0.8at% Cr: 0.1at%
40×70×10 mm

No.13 Material properties of ceramic Nd:Cr:YAG

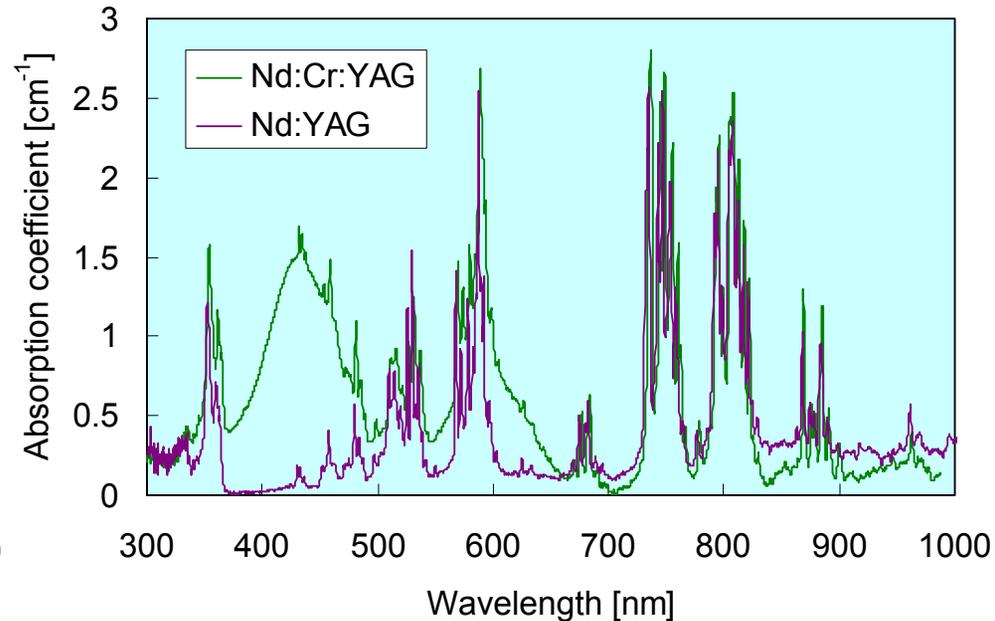


ILE OSAKA

Transmission spectrum



Absorption coefficient

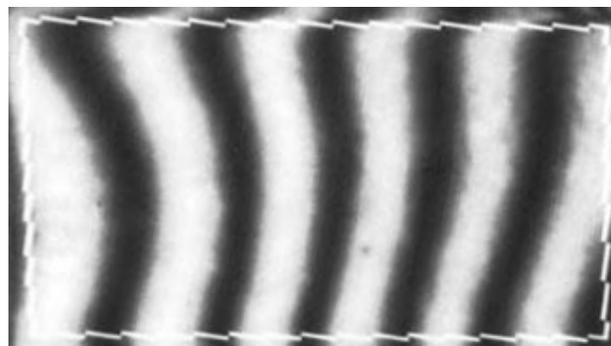


Absorption of lamp radiation

Nd:YAG 14%

Nd:Cr:YAG 42%

Transmission wave-front using He-Ne laser



PV 0.326λ

RMS 0.058λ



Physical parameter	Coolant			
	He gas	Pure water	FC-40	HT-110
Density [kg/m ³]	0.176	997.000	1870	1720
Viscosity [g/cm sec]	0.000194	0.010	0.041	0.014
Kinematic viscosity [cm ² /sec]	0.141	0.010	0.022	0.008
Volume flow rate [liter/min]	4000	40	40	40
Specific heat [J/gK]	5.195	4.186	1.047	0.963
Thermal conductivity [W/m□K]	0.0260	0.5686	0.0711	0.065
Reynolds number	1809	1989	910	2403
Prandtl number	0.68	7.35	60.29	21.18
Nusselt number	5.38	5.38	7.34	39.19
Surface heat transfer coefficient [W/cm ² □K]	0.080	0.308	0.052	0.255

Temperature gap between coolant and material surface

$$T_C = T_F + \frac{P_a t}{4FK} + \frac{P_a}{Fh}$$

Temperature Gap

.Pa=160W.

He	.35.7.
Pure water	.9.3.
FC-40	.54.9.
HT-110	:11.2.

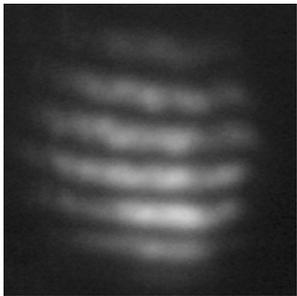
Temperature gap between center and surface of material

No.15 Wave-front distortions depend on liquid flow rate



ILE OSAKA

Initial pattern



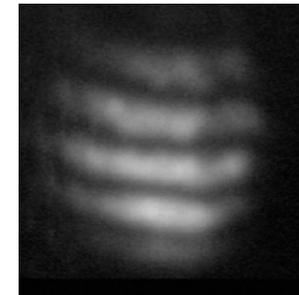
PV
 0.48λ

RMS
 0.091λ

18.9 L/min

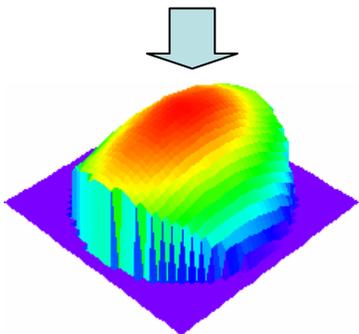


27.5 L/min

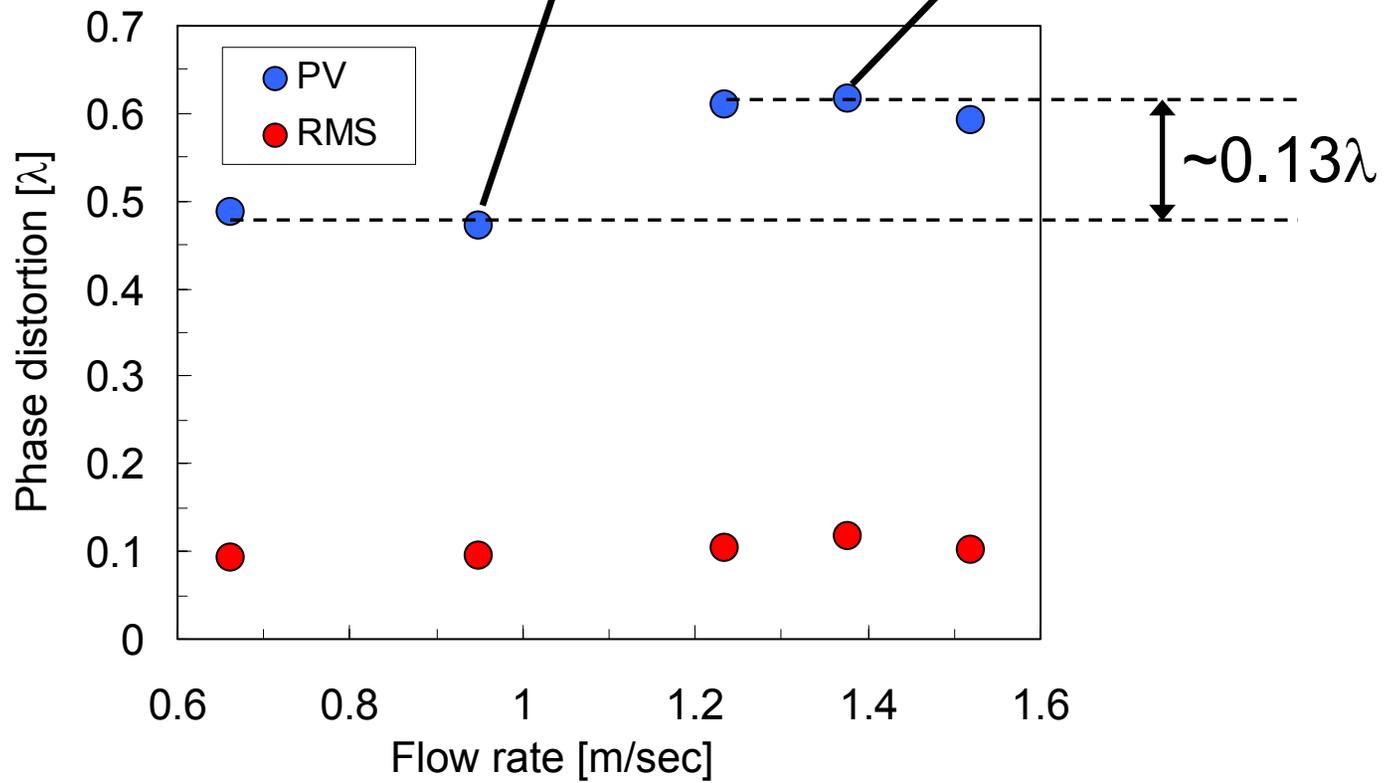


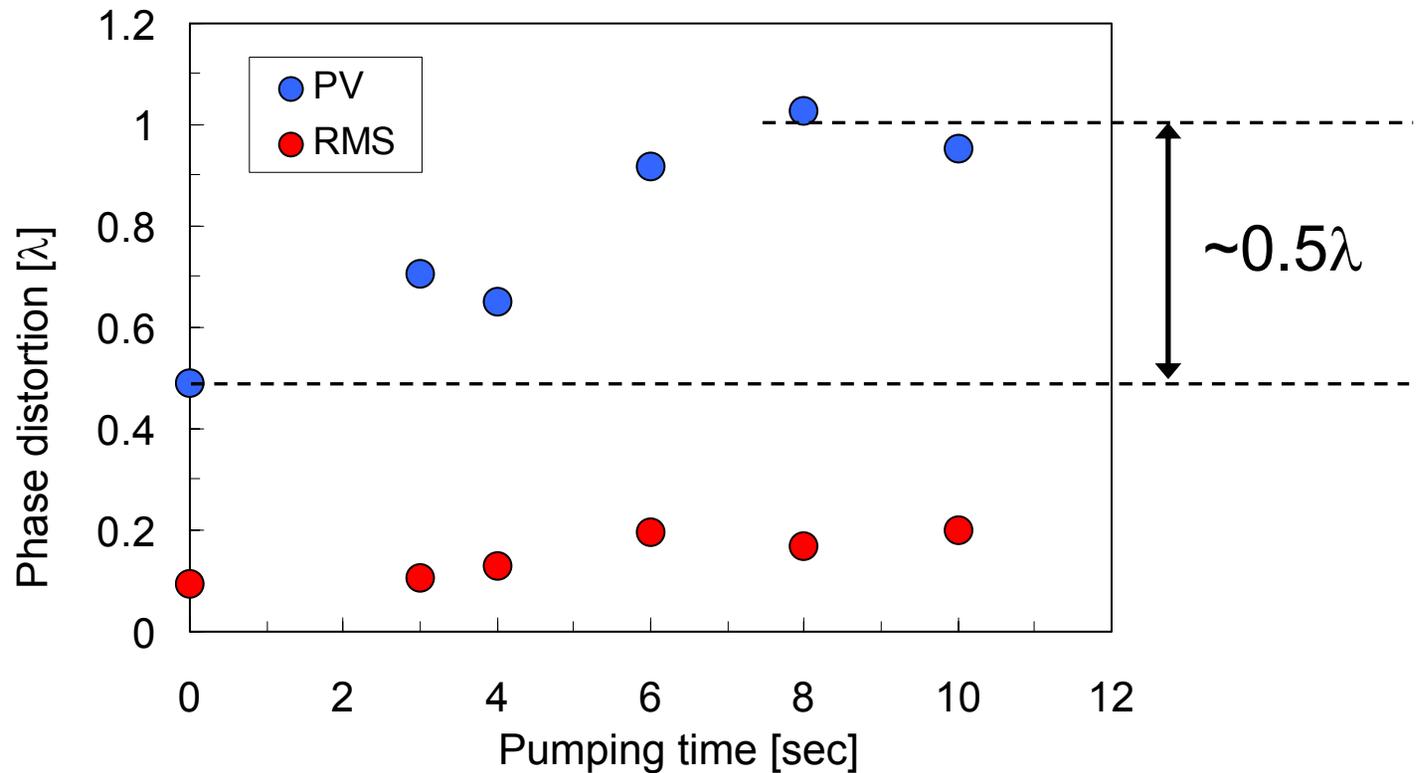
$$\phi(x, y)$$

Spatial phase distribution

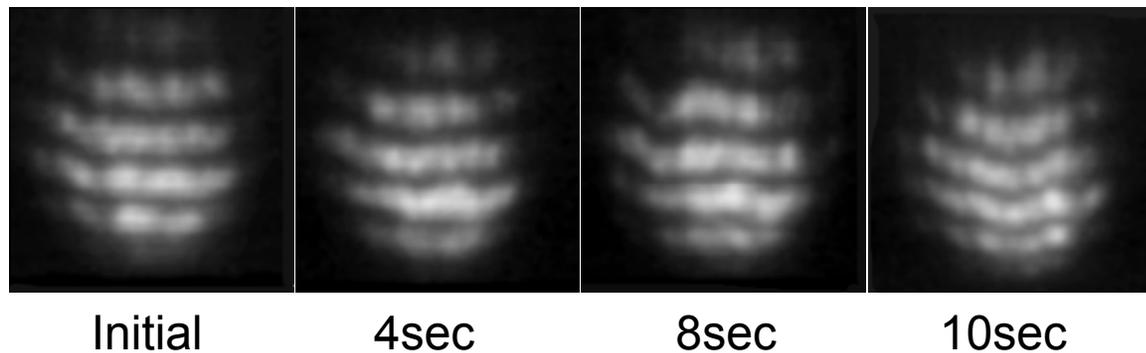


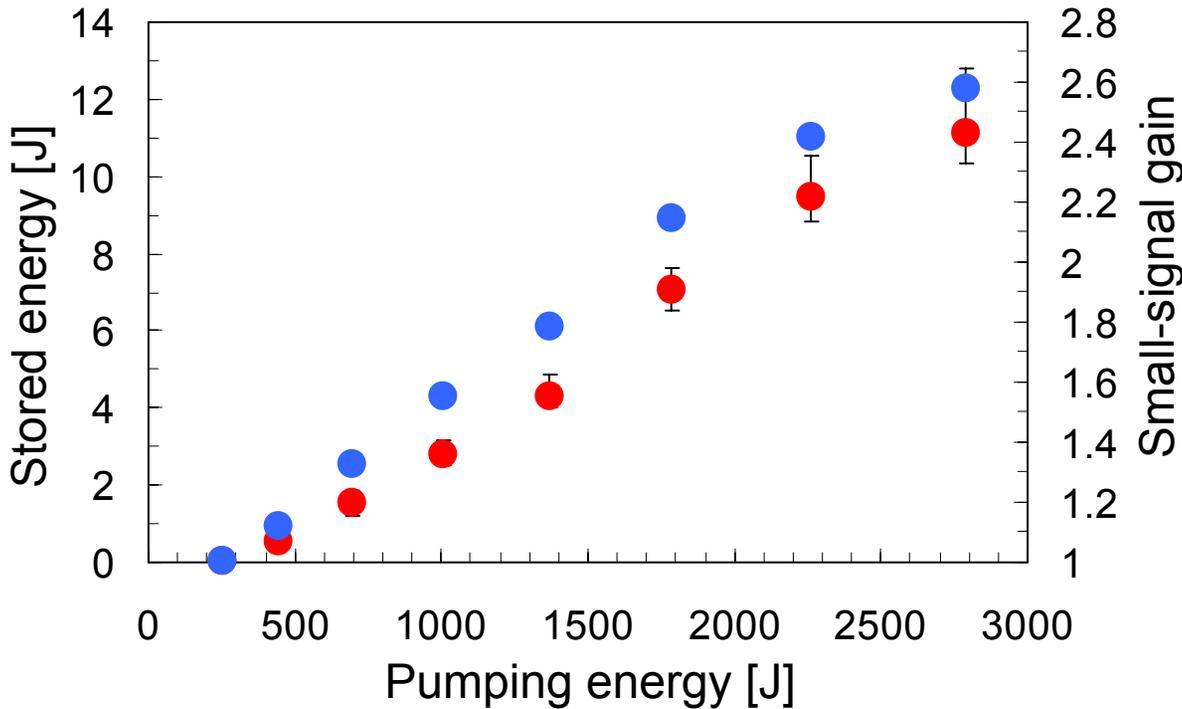
Wavefront





Absorbed power
 ~ 640 W
(10Hz, 4disks)



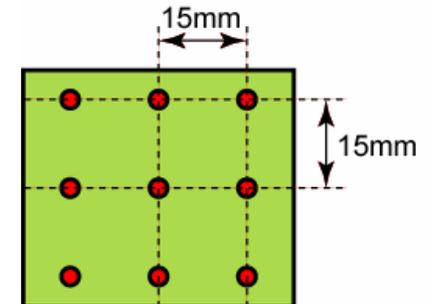


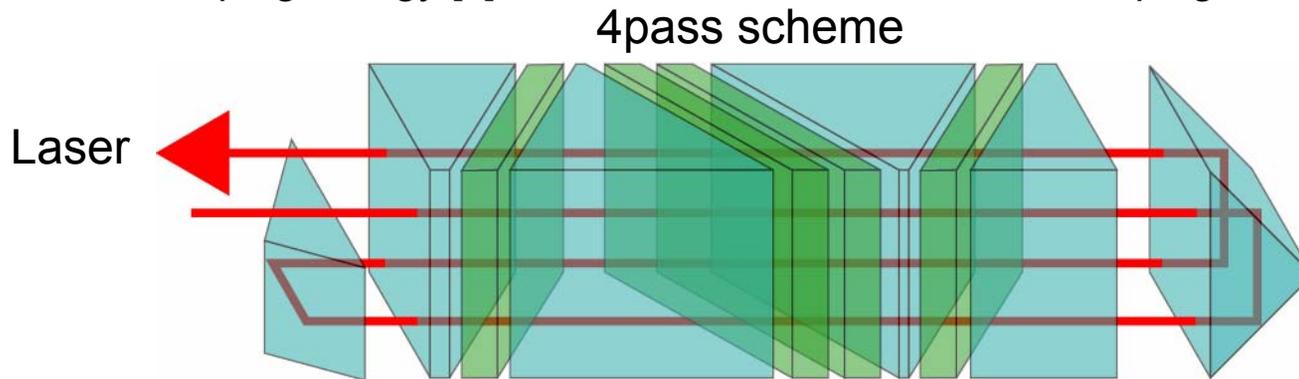
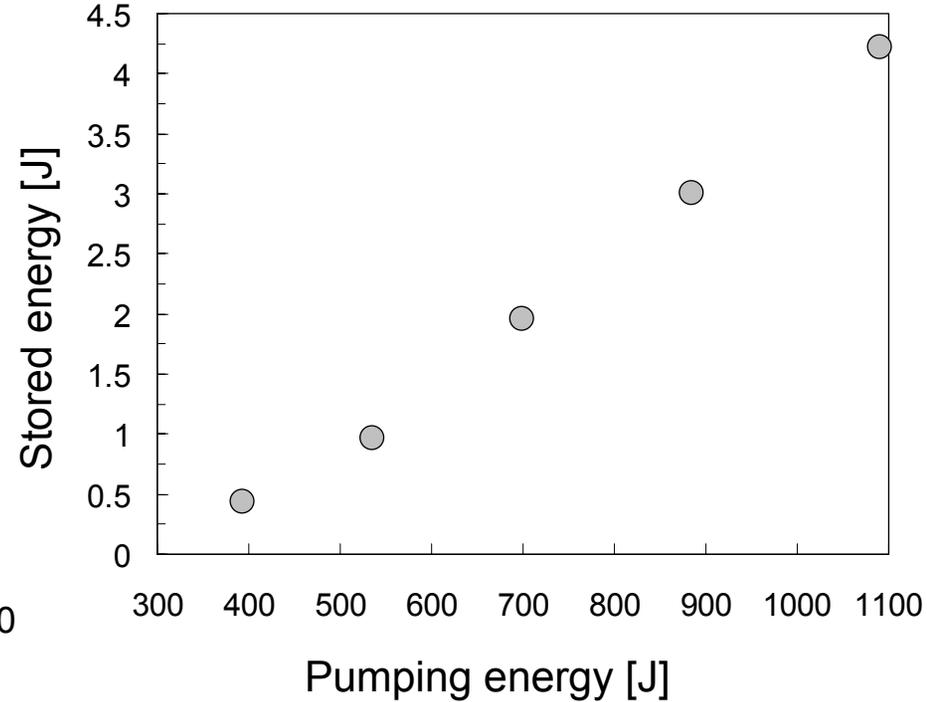
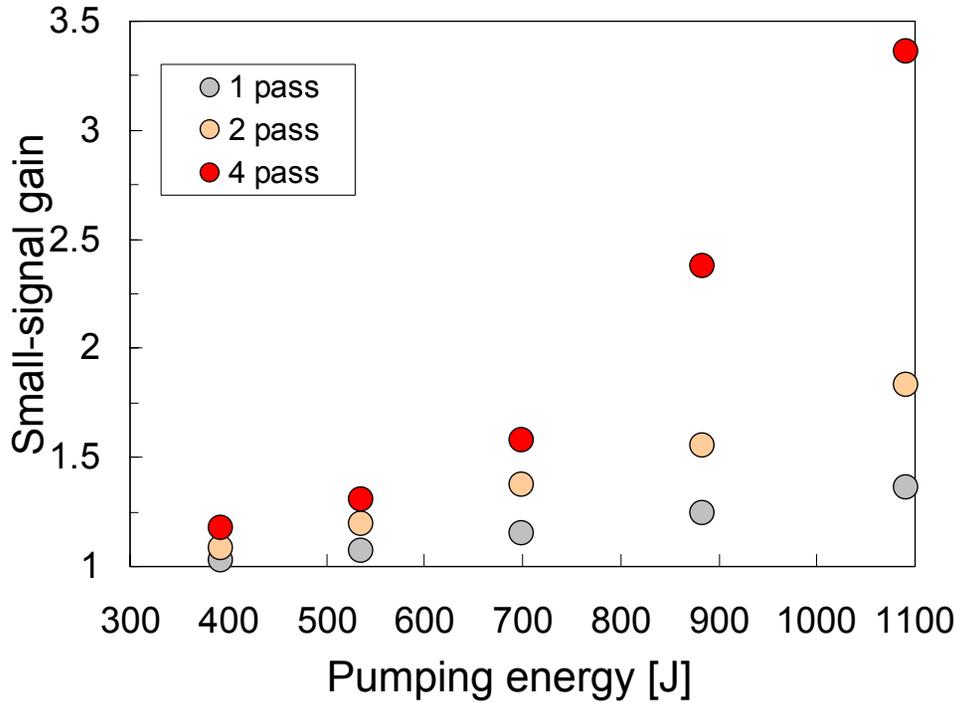
Max. Small-signal gain
2.44 (0.182cm⁻¹)

Max. Stored energy
12.3 J (0.113 J/cc)

Gain distribution ±8%

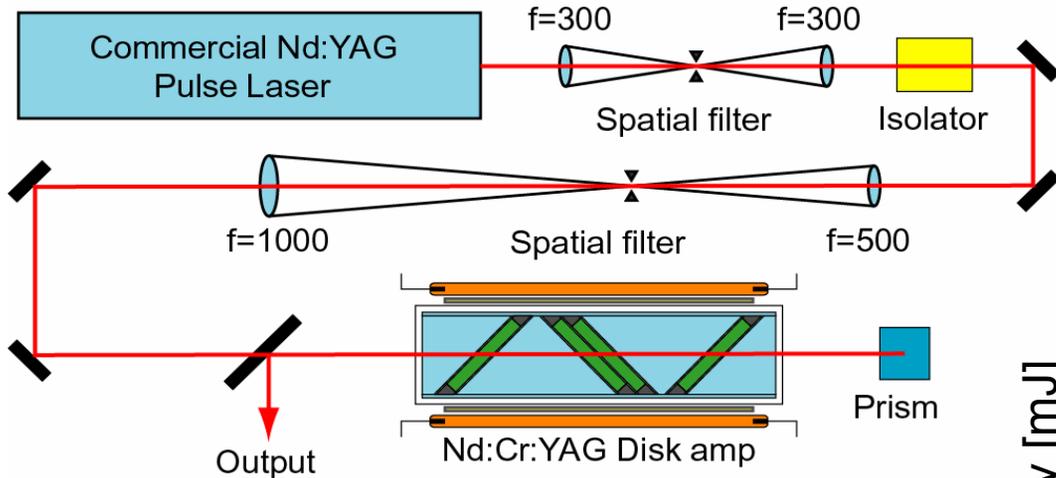
Parasitic oscillation limit $g_0L > 1.8$



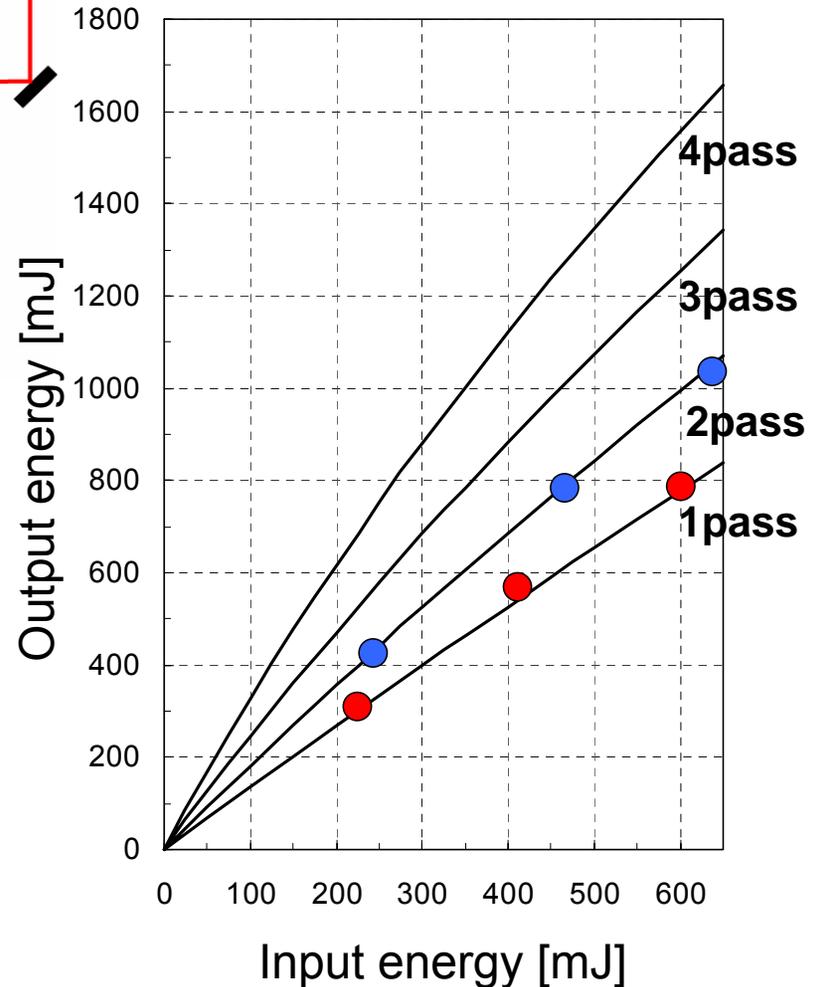
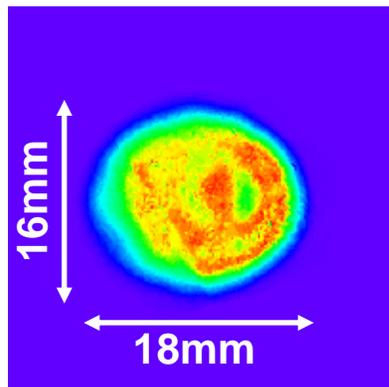




2pass amplification experimental setup



2pass amplification NFP





- Wavefront distortion due to coolant pressure

Michelson interferometer

Far-field pattern

Bifocal lens effect

Phase conjugation mirror

A green arrow pointing downwards from the text 'Phase conjugation mirror' to the text 'Phase error 1.7λ(ΔPV)'. The arrow has a white outline and a green fill.

- Phase error $1.7\lambda(\Delta PV)$, FFP spot size(620×1570mm) can be compensated into 1.2 times initial beam quality
- Small signal gain properties
Maximum Gain 2.0 and Stored energy 11.1J at 5.2kJ bank energy
(Gain coefficient 0.15cm^{-1})
- Single-shot amplification energy
Achievement of 10.4J output energy
(Extraction efficiency 42%, Gain 1.5)



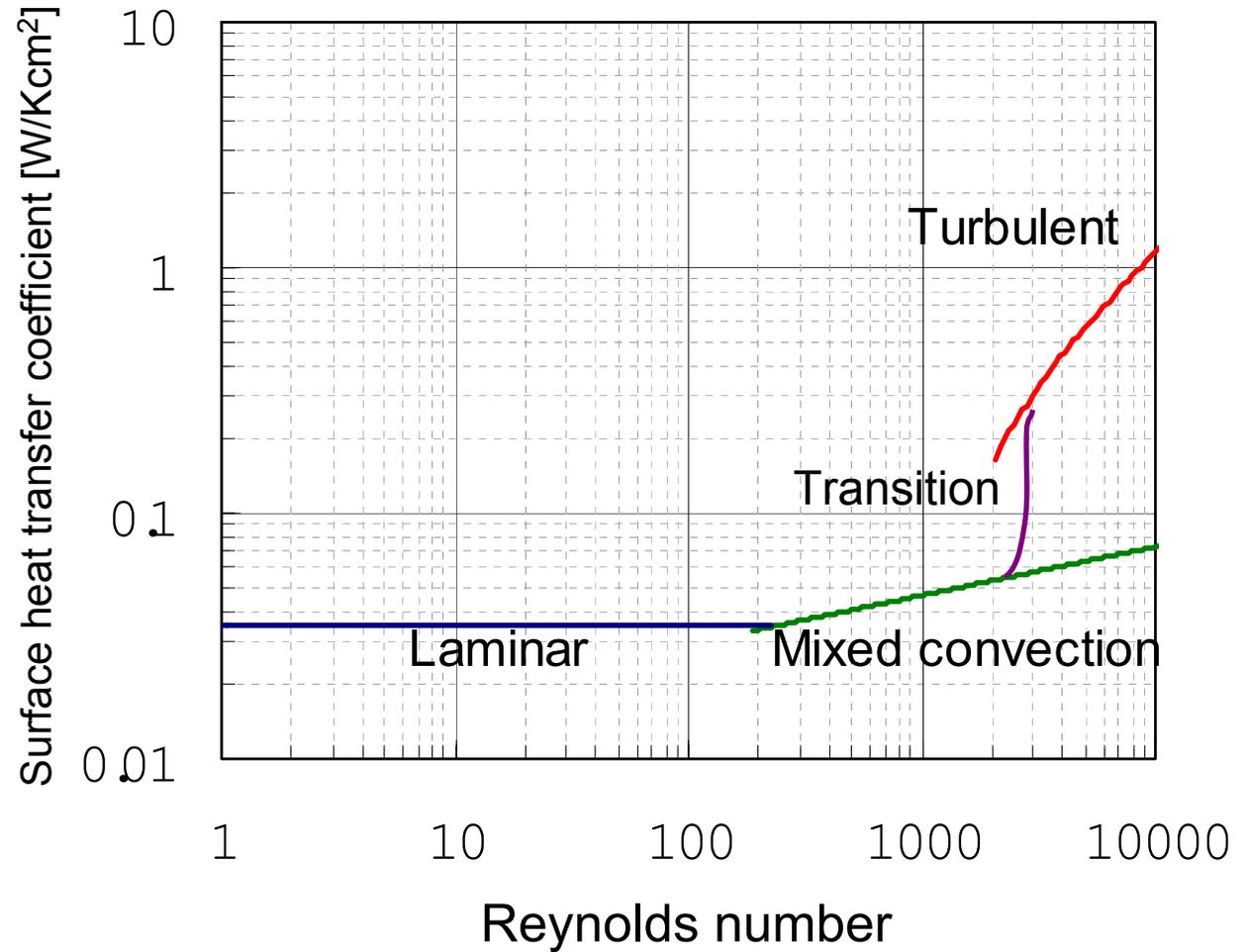
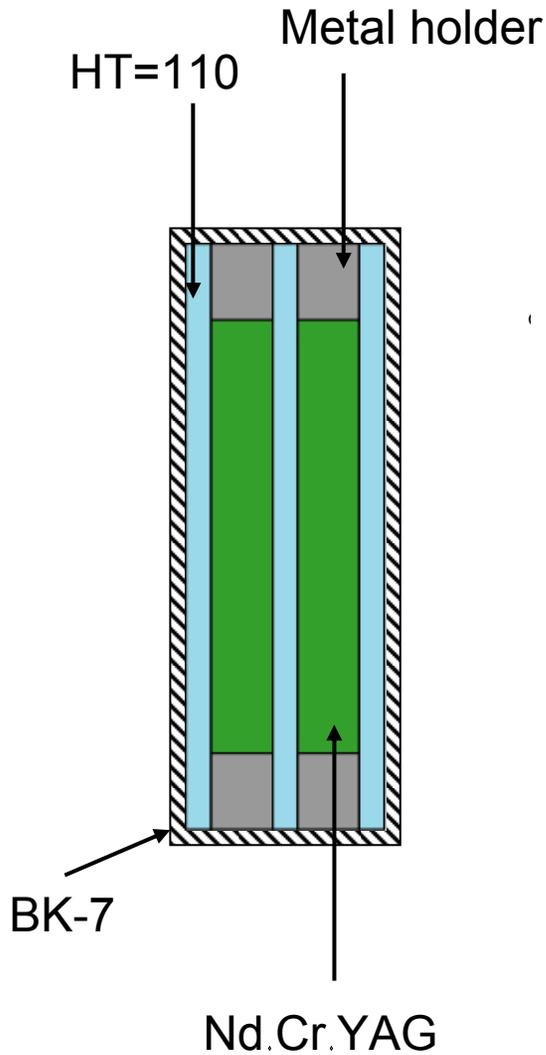
■ Development of Liquid face-cooled Split-disk Nd:Cr:YAG Laser Amplifier

- Measurement of properties of ceramic Nd:Cr:YAG
 - Transmission spectrum and wave-front
 - Amplifier properties
 - Calculation of Surface heat transfer coefficient at square channel
 - Temperature gaps are estimated
 - Wave-front measurement
 - Coolant flowing and transient variation at pumping
 - Single-shot operation
 - Max. gain **2.44** (gain coefficient 0.182 cm^{-1})
 - Max. stored energy **12.3 J** (energy density 0.113 J/cc)
 - 10Hz 2pas amplification **1.04 J** (output energy)
-
- ## ■ Future work
- Measurement of FFP, M^2
 - 4pass amplification

Cooling ability of HT-110



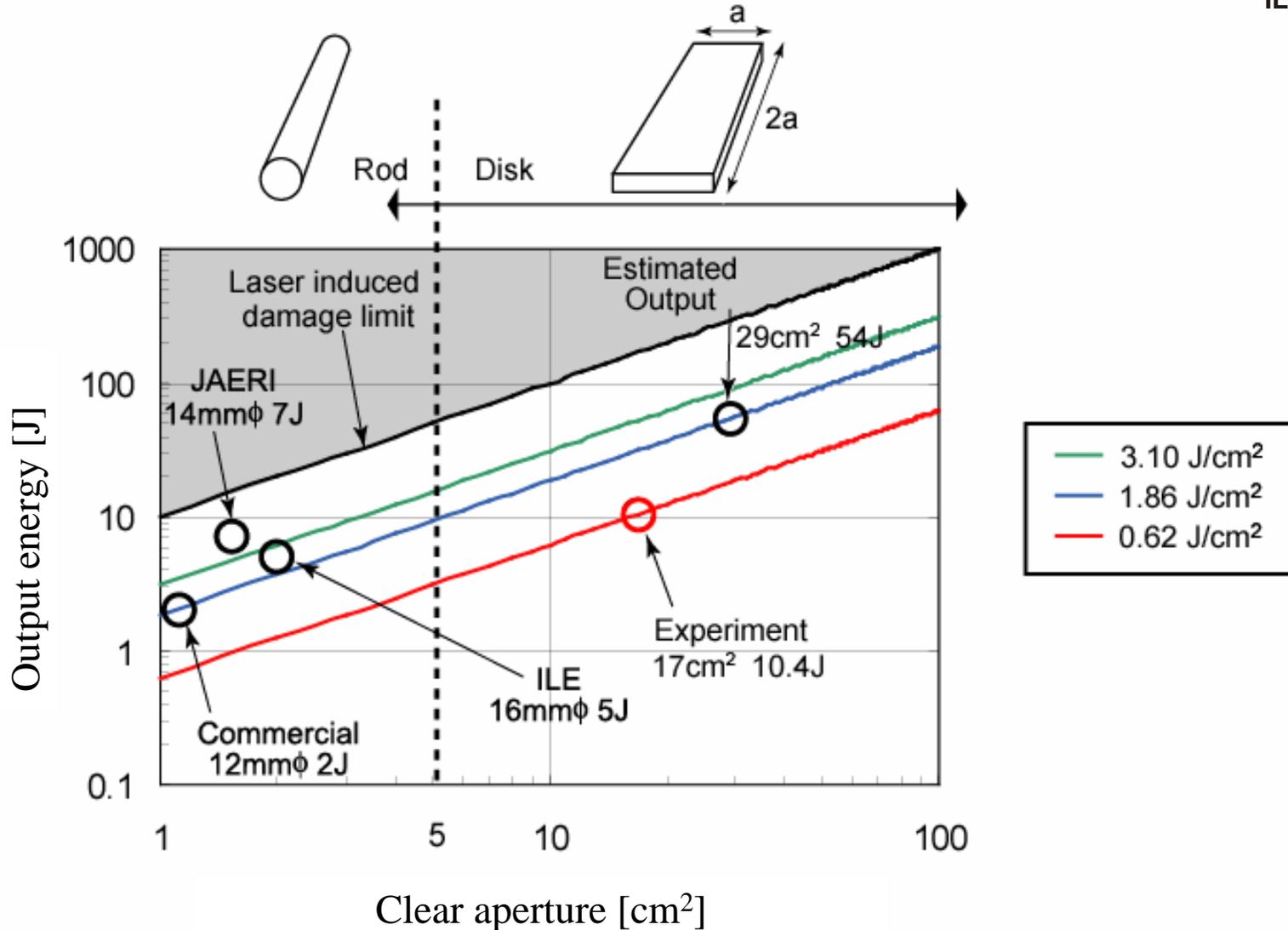
ILE OSAKA

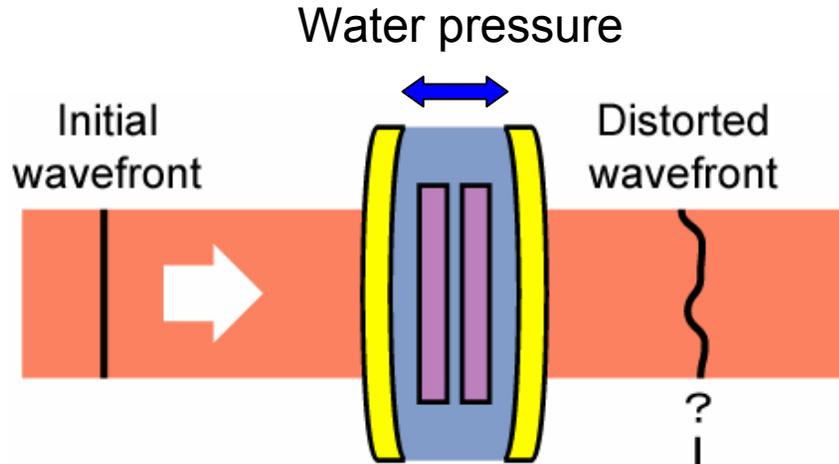




Estimation of output energy for Nd:YAG Q-sw laser

ILE OSAKA

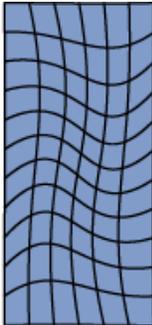
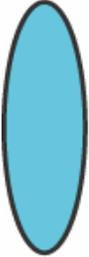




Estimation for wavefront distortion

Measurement of transmission wave-front

Lens effects ?



Distribution

- Flow rate
- Density
- Refractive index

Michelson interferometer

Far-field pattern

Wavefront compensation